

Channel Alignment And Radiometry In Hyperspectral Atmospheric Infrared Sounders

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ABSTRACT

The Atmospheric Infrared Sounder (AIRS) is a hyper-spectral infrared sounder which covers the 3.7 to 15.4 micron region with 2378 spectral channels. The AIRS instrument specification called for spatial co-registration of all channels to better than 2% of the field of view. Pre-launch testing confirmed that this requirement was met, since the standard deviations in the centroids was about 1% of the 13.5 km IFOV in scan and 3% in track. Detailed analysis of global AIRS data show that the typical scene gradient in 10 micron window channels is about 1.3K/km rms. The way these gradients, which are predominantly caused by clouds, manifest themselves in the data depends on the details of the instrument design and the way the spectral channels are used in the data analysis. AIRS temperature and moisture retrievals use 328 of the 2378 channels from 17 independent arrays. As a result, the effect of the boresight misalignment averages to zero mean. Any increase in the effective noise is less than 0.2K. Also, there is no discernable performance degradation of products at the 45 km spatial resolution in the presence of partially cloudy scenes with up to 80% cloudiness. Single pixel radiometric differences between channels with boresight alignment differences can be appreciable and can affect scientific investigations on a single 15km footprint scale, particularly near coastlines, thunderstorms and surface emissivity inhomogeneities.

1. INTRODUCTION

The modern generation of hyperspectral infrared atmospheric sounders features high spectral resolution and very low sensor noise. The improved performance of such instruments places much stiffer requirements on certain aspects of instrument design compared to earlier sounders. In this paper we will concentrate on spatial response issues—in particular, relative boresight alignments of different channels. An overview of the AIRS instrument and pre-flight test program and the pre-launch performance characteristics can be found in the literature (reference 1 and 2). We show that the degree of radiometric error in the difference between two channels is proportional to the amount of misalignment between channels.

This paper uses the Atmospheric Infrared Sounder (AIRS) on NASA's EOS Aqua spacecraft to demonstrate our point. AIRS had a very stringent specification for boresight alignment. For every possible pair of channels, the spatial responses had to agree to 99% or better. This paper discusses results of the pre-launch spatial alignment tests relative to the requirements. The AIRS design enables quantitative analysis of channel misalignments using on-orbit data. This feature is available on any hyperspectral infrared sounder. There are pairs of channels in which the two detectors are sensitive to the same frequency, or to similar frequencies that have closely matching infrared transmission properties, but have quite different locations on the focal plane. This paper uses such pairs, and a typical scene of the Indian Ocean at night, to perform quantitative analysis of the effect of misalignment on radiometry.

2. AIRS INSTRUMENT DESCRIPTION

The AIRS was built by BAE Systems, in Lexington Massachusetts, as system contractor for the AIRS Project at the Jet Propulsion Laboratory (JPL). It was launched on May 4, 2002 in a 705 km altitude polar orbit and is currently in routine operations. It is one of the instruments on board the Aqua spacecraft, which is the second of three satellites comprising NASA's Earth Observing System (EOS). The AIRS' purposes are to study the global water and energy cycle, study the

distribution and variability of water vapor in the atmosphere, to generate a climate data record useful for climatological studies, improve weather prediction, and to analyze trace gases, including a global map of atmospheric carbon dioxide.

The AIRS is a grating spectrometer with 2378 infrared channels sensitive from $3.75\ \mu$ to $15.4\ \mu$. Its spectral resolution is better than 1200 for all channels. The field of view for the infrared channels is 1.1 degree. The design of the optics and the focal plane determine the spatial response. Figure 1 shows the optics. Figure 2 shows the layout of the focal plane.

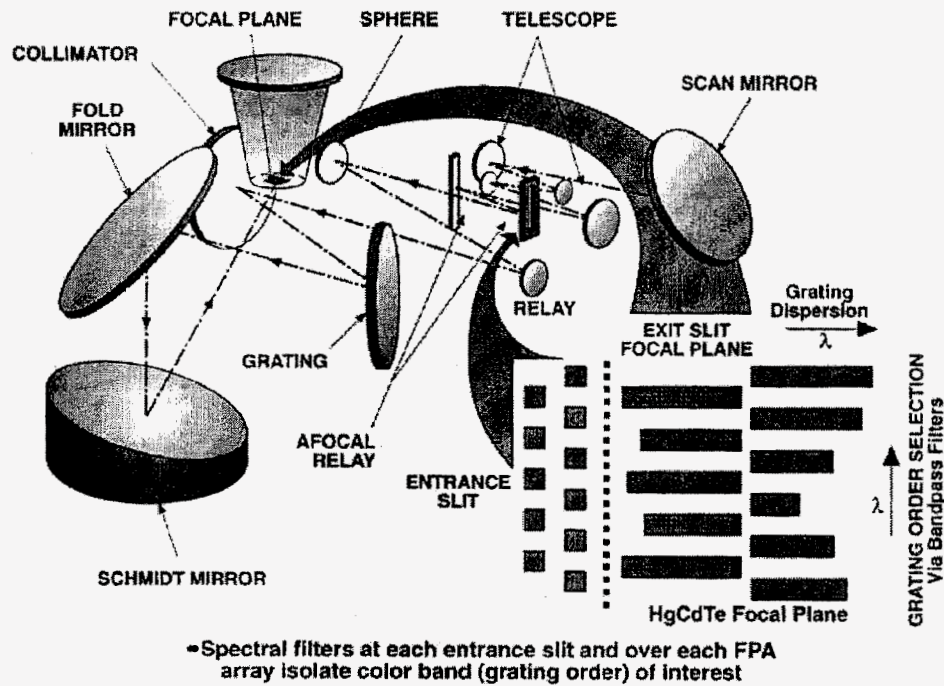


Figure 1 Schematic of the AIRS Optics

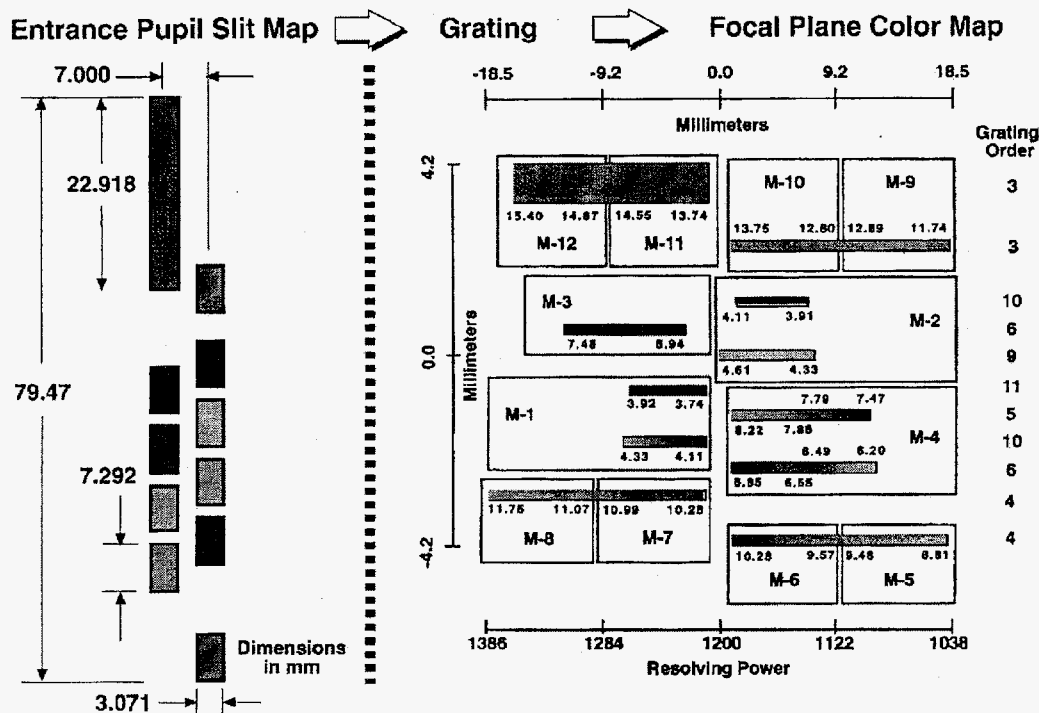


Figure 2 The AIRS Focal Plane Detector Layout

Note that there are 17 linear detector arrays, distributed among 12 modules, spread out in two dimensions on the focal plane. Multiple orders of the grating output are used. Each detector array has an order-isolation filter immediately above the detectors. In general, lower-numbered detector arrays are at shorter wavelengths, although there are some exceptions. This arrangement leads to several cases where two detectors are in different arrays at significantly different places on the focal plane, but with essentially the same wavelength sensitivity. This aspect of the AIRS design is used in Section 5 to study the effects of channel boresight alignment in detail.

3. PRELAUNCH SPATIAL RESPONSE MEASUREMENTS AND ANALYSIS

Complete AIRS spatial response measurements were made prior to launch in the AIRS Calibration and Test Facility at BAE Systems. A 1400 K blackbody was used as the light source. A custom-made Spatial Collimator System (SCS) was used to ensure that the blackbody appeared as a point source. The beam was then passed through the entire AIRS optical system to the flight focal plane (except that the scan mirror had been removed). The SCS could be controlled to move the point source in two dimensions within the field of view. Measurements were made at every point in a 39x39 array whose center was the nominal boresight. The point spacing was 0.04 degrees, so a 1.52 by 1.52 degree area was measured. Thus, the spatial response of every channel was measured over a 1.52-degree square (nominal field of view is 1.1 degrees). For details of the test setup and test procedure, see reference 3.

Figure 3 shows the measured response, referred to as the "top hat function", for a typical detector.

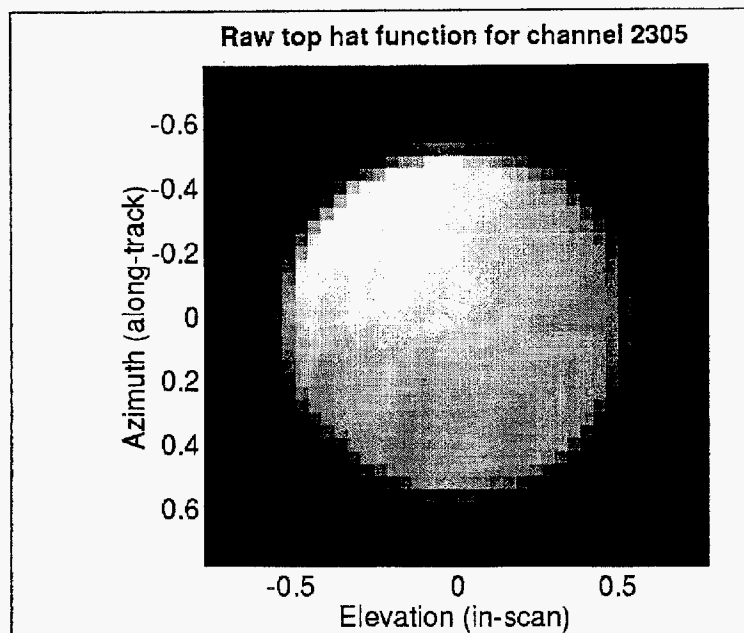


Figure 3 Two-Dimensional Spatial Response Of A Typical AIRS Channel (Without Field Stop)

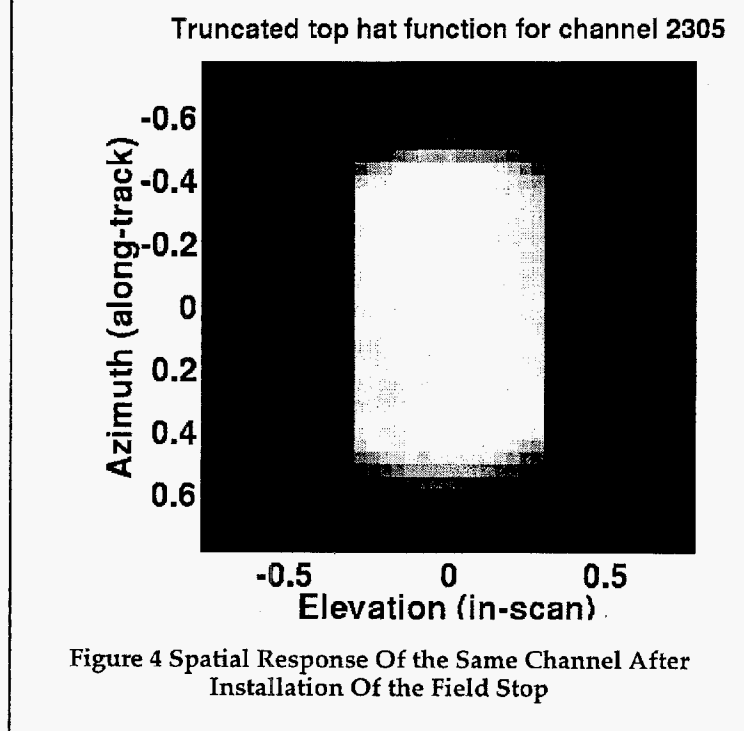


Figure 4 Spatial Response Of the Same Channel After Installation Of the Field Stop

The complete $39 \times 39 \times 2378$ set of measurements was made prior to one hardware change to the optics. A field stop was added to increase the f-number of the optical system, thereby increasing the depth of field. That change truncated the spatial response in the in-scan direction to about one-half of the original (0.60 degrees). A partial set of new spatial response measurements was made with the field stop in place, to confirm that its effect was as expected. Figure 4 shows the top hat function for the same typical detector after the field stop was added. Rather than repeating the entire test, top hat functions were calculated for all detectors by truncating the measured functions, removing left-hand and right-hand columns to produce a 39×15 array for each detector. As expected, the centroid offsets in the y-direction were noticeably reduced by the introduction of the field stop. But they were not eliminated.

Differences between the centroids of the resultant top hats are good indicators of the alignment of the boresights of the individual detectors. Figure 5 shows a plot of the X (cross-scan) and Y (in-scan) centroid coordinates for all detectors. Note that most of the centroids are randomly distributed (relative to the common geometric boresight) with a standard deviation of 0.016 degrees in-scan and 0.031 degrees along-track relative to the common boresight. The far outliers fall mainly into two classes: detectors near the ends of arrays that are partially shadowed by a focal plane mask used to hold the order-isolation filters; and detectors with unusually high noise at the time the measurements were made. Systematic changes across some detector arrays are AIRS pupil-imaging-unique focal plane illumination effects.

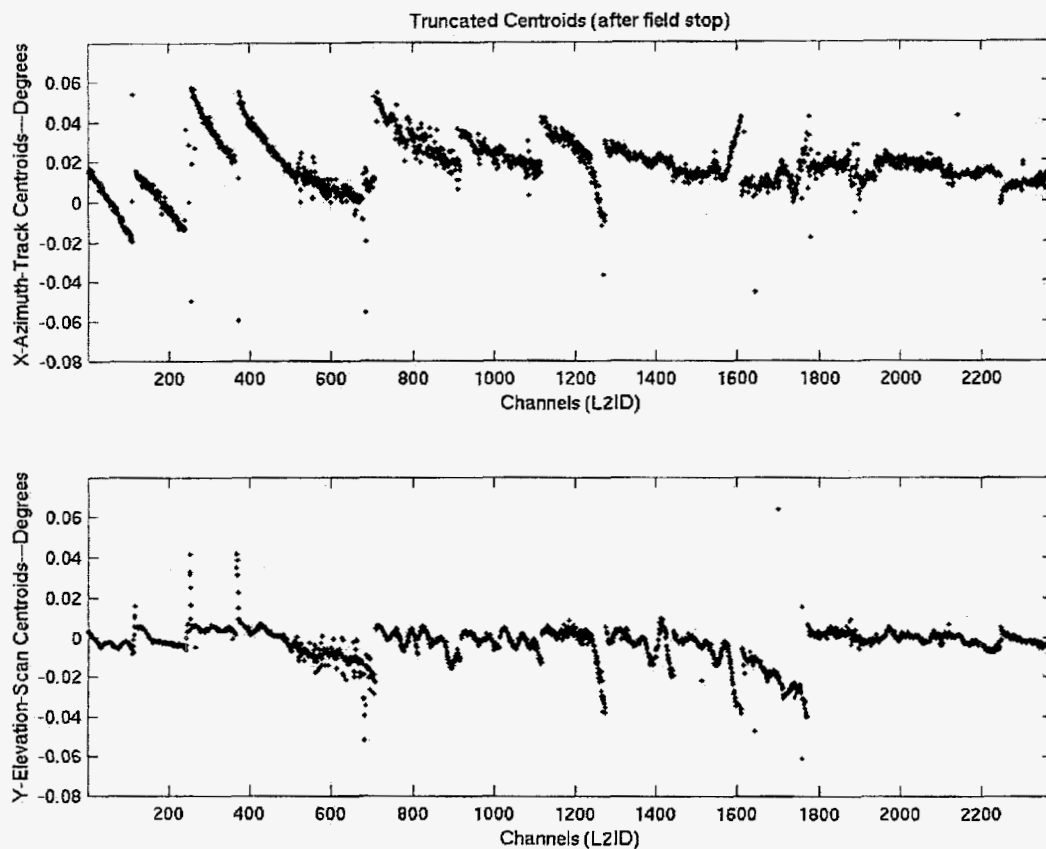


Figure 5 AIRS Spatial Response Function Centroid Coordinates

4. IMPACT OF MISALIGNMENTS ON AIRS SCIENCE RESULTS

Routine AIRS science results include radiances at each channel at each footprint and atmospheric temperature and humidity profiles. The radiances, besides being inputs for calculation of the profiles, are used by NOAA and other agencies in their weather prediction software. Use of AIRS radiances has significantly improved weather forecasts in both hemispheres (references 4 [Atlas] and 5 [Le Marshall]).

The temperature profiles are calculated at each footprint of the Advanced Microwave Sounding Unit A (AMSU-A). An AMSU-A is flying on Aqua and is also in routine operations. Its field of view is 3.3 degrees. So (typically) nine AIRS spectra from nine AIRS footprints that overlap one AMSU-A footprint are combined during profile retrievals. Hundreds of channels are used during the retrievals, and none of them are outliers in Figure 4. Barnett (reference 6) has performed a detailed analysis that shows the (typical) misalignments have negligible impact on retrieval accuracies. He has examined the cloud clearing rejection statistics and sees no correlation with the radiometric difference between pairs of overlap channels.

5. INDIAN OCEAN SCENE GRADIENT ANALYSIS

As was noted in Section 2, there are pairs of detectors well separated on the focal plane but with essentially the same frequency response. Such frequency-overlapping pairs are at the ends of detector arrays, where boresight misalignment amounts tend to be largest. The offsets can be as large as 1 km in the 13.6 km nadir footprints. One such channel pair consists of detector 2254, in Module 2A (M-02-a), and detector 2282, in M-01a. These are window channels with frequencies near 2563 cm^{-1} . Channel 2254 has a top hat function whose centroid is at $x = -0.1351$, $y = 0.0162$ (degrees). The centroid of channel 2282 is at $x = -0.0145$, $y = -0.0025$. The discrepancy between their boresights, as indicated by these centroids, is 0.12 degrees in x —much larger than is typical for AIRS. These channels were used in coastline crossing analyses to verify and refine the AIRS pointing knowledge (reference 7).

This overlapping channels feature is unique to the AIRS instrument, and permits investigation of spatial calibration effects using observed brightness temperatures. For most instruments, studies have been forced to look at retrieved atmospheric properties. But there are so many variables involved that it has not been possible to reach firm conclusions about the effects of small spatial misalignments.

Channels at significantly different frequencies can be compared in a similar fashion, as long as the frequencies are such that the transmission to the surface in both channels is the same. We will now look at images created by taking the difference between two window channels. From image to image, the difference in boresight angles will steadily increase, from a well-aligned 0.005 degree difference to a poorly-aligned 0.09 degrees. Remember that the AIRS infrared footprint size is 1.1 degrees. All the images are of a typical night granule covering an area of about $1500 \times 1500\text{ km}$ in the Indian Ocean.

Such overlapping channels can be used to evaluate the effects of spatial gradients on the apparent scene brightness temperature. These gradients can be due to clouds or due to surface emissivity effects. In either case, the magnitude of these gradients establishes what constitutes adequate boresight alignment for hyperspectral sounders where the observed radiance is interpreted with the assumption that gradients are entirely due to atmospheric effects, not misregistration effects.

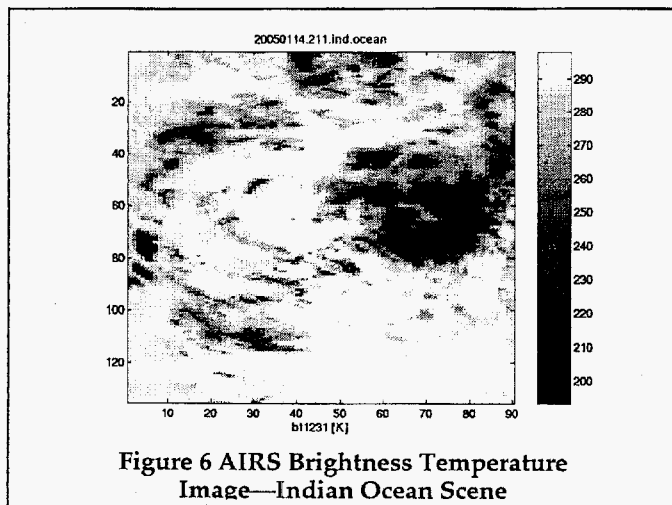


Figure 6 is an image made from AIRS channel 844 (frequency 1231 cm^{-1}), which is one of the best window channels. It is six minutes worth of data taken at night over the Indian Ocean on January 14, 2005. The temperature of the ocean surface is very uniform and close to 300K. Note the very cold feature (high cloud system with cloud tops near 210K) at the right, as well as other nearly circular clouds surrounding the main feature.

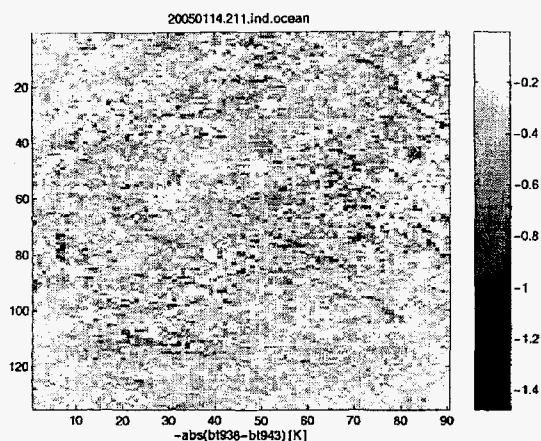


Figure 7

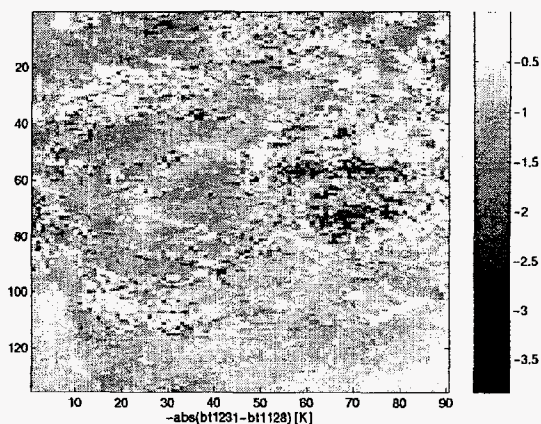


Figure 8

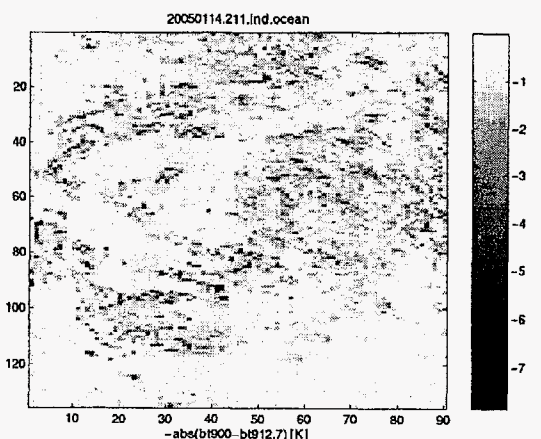


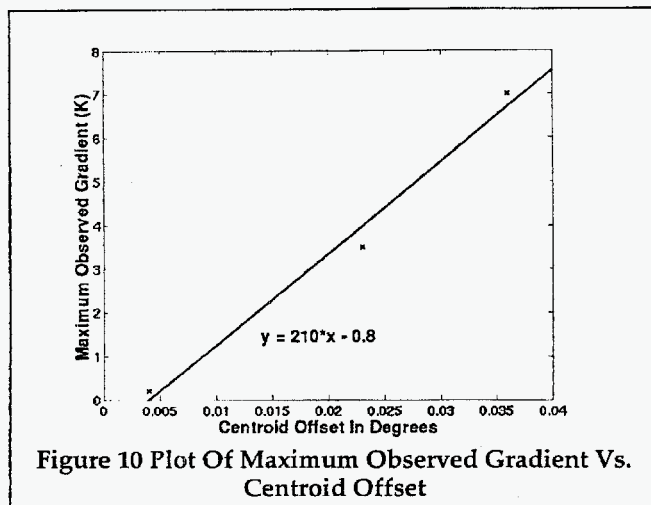
Figure 9

Figures 7, 8, and 9 show a sequence of difference images using three different pairs of AIRS window channels. There is a steady progression in these images from well-aligned channels in Figure 7 to channels with significant boresight offset in Figure 9. In each image the negative of the absolute value of the difference is shown. Since the differences are predominantly small, using the negative results in a lighter image, which makes features easier to see.

Figure 7 is the difference between AIRS channels 844 and 857 in detector module M-07. Their frequencies are 938 cm^{-1} and 943 cm^{-1} in closely matching atmospheric windows. These channels are aligned to within 0.004 degrees. The high cloud and some circular features are barely visible because we know what to look for, but note the temperature scale at the right. The mean gradient is small everywhere. The rms of 0.20K agrees well with what is expected from a Gaussian distribution (0.17K) for the difference between the two channels.

Figure 8 shows the brightness temperature difference between channels at 1231 cm^{-1} and 1128 cm^{-1} . These channels have boresights that agree to within 0.023 degrees. The features are clearly visible, and the difference values are much larger than in Figure 7. Gradients as large as $\pm 3.5\text{K}$ are seen at cloud boundaries.

Figure 9 shows the brightness temperature measured by channel 760 in M-08 (frequency 900.65 cm^{-1}) minus channel 774 in M-07 at frequency 912.65 cm^{-1} . These channels are aligned to within 0.036 degrees. See Table 1 below. The features are visible, and maximum gradients have grown to $\pm 7\text{K}$ along cloud boundaries. (Note the expanded temperature range on the scale at the right of the image.)



The maximum observed brightness temperature differences are closely proportional to the difference in the boresight, as illustrated in Figure 10. This allows us to discuss the effect in geophysical units in terms of a scene brightness temperature gradient. We will concentrate on the detector pair used in Figure 9. Both channels are window channels whose surface transmissions are matched within 0.2K. Table 1 summarizes the relevant properties of these channels. For Gaussian noise the rms difference between these two channels should be 0.25K. But the standard deviation of the difference image is 0.73K—it is dominated by the misalignment-induced gradients. The boresights differ by 0.036 degrees. This corresponds to about 450 meters from the EOS Aqua altitude of 705 km.. Thus, in this image there is a typical scene gradient of 0.73K in 450 meters. Based on analysis of all spectra for two entire days (September 6 2002 and

January 31 2005), the typical Gaussian equivalent standard deviation is approximately 0.6K. Thus the typical horizontal gradient is 1.3K/km for the AIRS 1.1 degree footprint. Note that gradients can easily be ten times this large near thunderstorms. Gradients for footprints which are smaller than the AIRS footprint may be proportionally larger.

Table 1 Properties of Channel 760/774 Pair

Channel #	Frequency (cm ⁻¹)	NEAT at 290K	x boresight (degrees)	y boresight (degrees)
760	900.65	0.17K	0.0093	-0.0109
774	912.65	0.18K	0.0369	-0.0348

Depending on details of the design of the instrument, and the data analysis, the presence of 1.3K/km rms scene gradients may result in systematic errors or it may average out, but manifest itself as scene noise. Since AIRS temperature and moisture retrievals use 328 of the 2378 channels, selected from 17 independent detector arrays, the effect of the boresight misalignment can be treated statistically, i.e. the combination of boresight misalignments and knowledge of the typical rms scene gradient, 1.3K/km, can be converted into an effective scene noise term. The rms deviation from the common boresight is 0.016 degrees in-scan and 0.031 degrees along-track. We use the mean value of 0.023 degree for the estimate of the noise. From 704 km altitude a misalignment of 0.023 degrees corresponds to a displacement of 0.28 km on the ground, which corresponds to a $0.28 * 1.3 = 0.36$ K rms effective noise. Since AIRS footprints are used in the temperature profile retrieval software in groups of 3x3, the scene noise is decreased by a factor of three to about 0.12K rms. This is well below the noise in most of the AIRS channels and much below other sources of noise which are inherent in a multichannel retrieval system. This explains why there is no correlation between gradients in a scene and the accuracy of the retrieval relative to RAOBs under as much as 80% cloud cover, as reported by Barnett (reference 6).

6. CONCLUSIONS

The AIRS instrument specification called for spatial co-registration of better than 2% of the fields of view of its 2378 spectral channels. Pre-launch testing confirmed a standard deviation in the centroids of about 1% of the 13.5 km IFOV in scan and 3% in track. AIRS data show that the typical scene gradient in 10-micron window channels is about 1.3K/km rms, which may result in systematic error or may cause scene noise. The way this scene noise manifests itself in the data is instrument design specific and also depends on the way the spectral channels are used in the data analysis. In the case of the AIRS the effective scene noise is less than 0.2K and results in no discernable performance degradation of

atmospheric temperature and moisture retrievals at the 45 km spatial resolution and in the presence of partially cloudy scenes with up to 80% cloudiness. Single pixel radiometric differences between channels with boresight misalignment differences can be appreciable and can affect scientific investigations on a single 15km footprint scale, particularly near thunderstorms.

7. REFERENCES

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